

PATENT

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TITLE: EFFICIENT PCM MODEM

FIELD OF THE INVENTION

5 The present invention relates to telecommunications and, more particularly, to
telephone modems.

BACKGROUND OF THE INVENTION

10 Modems are telecommunication devices used to transfer information between a first
digital device, e.g., a computer, and a communication medium, such as a twisted pair
telephone line, for communication with a second device at a telephone company central
office (TCCO), for example. In order to communicate with the TCCO, the modem must
perform a number of functions to ensure that the TCCO can interpret signals sent from the
modem and that the modem can interpret signals received from the TCCO. Generally, the
functions that the modem must perform are set forth in modem specifications developed by a
15 telecommunications standards organization such as the International Telecommunications
Union (ITU).

20 Modern modem specifications, such as the V.92 dial-up modem specification
developed by the ITU, set forth the functions that a modem in accordance with the
specification must perform. These functions may include: modifying the phase and timing of
the outgoing and incoming communication signals, canceling echos on incoming
communication signals, and matching code sampling rates through interpolation and
decimation.

Many of the functions that a modem performs are accomplished via software running on a digital signal processor (DSP). Typically, these functions require a great deal of processing by the DSP, which uses processing power that could be utilized for other tasks. Accordingly, there is a need for apparatus and devices capable of performing the functions of a modem more efficiently, thereby freeing processing power for performing other tasks. The present invention fulfills this need among others.

SUMMARY OF THE INVENTION

The present invention provides for efficient apparatus and methods to perform modem functions, which overcome the aforementioned problems. Efficiencies are achieved in the present invention through the use of computationally efficient phase shifters, echo cancelers, and timing recovery devices. In addition, efficiencies can be achieved by reducing the number of interpolators and decimators that adjust sampling rates within the modem by incorporating their function into other apparatuses within the modem.

One aspect of the present invention is a modem for establishing communication between a first device and a second device via a communication medium, the modem being coupled to the communication medium through a hybrid circuit to pass a transmit signal generated by the first device via a transmitter to the communication medium and pass a receive signal from the communication medium to a receiver for processing by the first device. The modem includes a Farrow phase shifter positioned between the first device and the hybrid circuit to shift the phase of the transmit signal; an equalizer having an adaptive input positioned between the hybrid circuit and the first device to minimize intersymbol interference in the receive signal; a primary echo sub-canceler having an input coupled

between the Farrow phase shifter and the hybrid circuit to receive the phase shifted transmit signal and an output coupled between the hybrid circuit and the equalizer to remove a first portion of an echo in the receive signal; a post equalizer echo canceler having an input coupled between the Farrow phase shifter and the hybrid circuit to receive the phase shifted
5 transmit signal and an output coupled between the equalizer and the first device to remove a second portion of the echo in the receive signal, the post equalizer echo canceler having an adaptive input; and a slicer positioned between the output of the post equalizer echo canceler and the first device, the slicer having an output for producing a standard symbol value which is a representation of a current symbol value being supplied at an input by the receive signal, the difference between the input and the output of the slicer being supplied to the adaptive input of the equalizer and to the adaptive input of the post equalizer echo canceler.

Another aspect of the invention is a method for use in a modem to establish a communication between a first device and a second device via a communication medium, the modem being coupled to the communication medium through a hybrid circuit to pass a
15 transmit signal generated by the first device via a transmitter to the communication medium and pass a receive signal from the communication medium to the first device via a receiver. The method includes the steps of shifting the phase of the transmit signal using a Farrow structure; generating a first echo estimate signal from the phase shifted transmit signal using a sub-canceler echo canceler structure; generating a second echo estimate signal based on the
20 phase shifted transmit signal and an adaptive signal using an infinite impulse response filter; converting the transmit signal from digital to analog at a sampling rate; passing the analog transmit signal to the hybrid circuit; receiving a receive signal from the hybrid circuit; converting the receive signal from the hybrid circuit from analog to digital at the sampling

rate; subtracting the first echo estimate signal from the receive signal; adjusting the sampling rate based on the receive signal after subtracting the first echo estimate signal; equalizing the receive signal based on the adaptive signal; subtracting the second echo estimate signal from the equalized receive signal; slicing the equalized receive signal for processing by the first
5 device via the receiver; subtracting the receive signal prior to slicing from the downstream data stream after slicing to generate the adaptive signal.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a computationally efficient modem in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 depicts a block diagram of a computationally efficient modem for establishing communication between a first device, e.g., a DSP 104, and a second device, e.g., a device at a TCCO 100, via a communication medium such as a twisted pair telephone line 102. In a
15 general overview, an upstream data stream produced by a digital signal processor (DSP) 104 is passed through a transmitter 106, a Farrow phase shifter 108, an interpolator 110, a coder/decoder (CODEC) 112, and a hybrid circuit 114 to create a transmit signal for transmission over the twisted pair telephone line 102 to the TCCO 100. A receive signal
20 received from the TCCO 100 over the twisted pair telephone line 102 is passed through the hybrid circuit 114, the CODEC 112, a decimator 116, a fractionally spaced equalizer 118, a slicer 120, and a receiver 122 to yield a downstream data stream for processing by the DSP 104. Equalization of the receive signal is performed by the fractionally spaced equalizer

(FSE) 118 and a decision feedback equalizer (DFE) 124. Echoes on the receive signal are removed through the use of a computationally efficient combination of a primary echo sub-canceller (PESC) 126 and a post equalizer echo canceler (PEEC) 128. In addition, the timing of the CODEC 112 is adjusted through the use of a phase locked loop (PLL) 130.

5 FIG. 1 will now be described in detail. An upstream stream of data for transmission is supplied to the transmitter 106 by the DSP 104. It is understood that the DSP 104 may be essentially any device capable of processing signals. The transmitter 106 scrambles and encodes the bits within the stream of data in a known manner. Thereafter, the encoded data is mapped and modulated to generate a transmit signal that represents a version of the encoded stream of data.

10 The transmit signal out of the transmitter 106 is phase shifted by a Farrow phase shifter 108. The phase of the transmit signal is shifted such that a signal, which is based on the transmit signal, received at the TCCO 100 has an appropriate phase. The necessary phase shift introduced by the Farrow phase shifter 108 is calculated at the TCCO 100 and
15 transmitted from the TCCO 100 to the modem using known training protocol.

20 The Farrow phase shifter 108 is a phase shifter that incorporates a Farrow structure. A Farrow structure can be easily implemented by the DSP 104 to perform phase shifting of the transmit signal. In addition, Farrow structures are computationally efficient, thereby minimizing memory requirements and the number of instructions per second required from the DSP 104 to shift the phase of the transmit signal. An example Farrow structure is of a type described in an article entitled "A Continuously Variable Digital Delay Element," IEEE International Symposium on Circuits and Systems, (ISCAS 1988), Jun. 6-9, 1988, pages 2641-2645, incorporated fully herein by reference. Also, see U.S. Patent No. 4,866,647

issued to Cecil W. Farrow on September 12, 1989, incorporated fully herein by reference. The adaptation of a Farrow structure to shift the phase of a transmit signal will be readily apparent to those skilled in the art.

The transmit signal out of the Farrow phase shifter 108 is interpolated by an interpolator 110. The interpolator 110 converts the sample rate of the phase shifted transmit signal to a common sample rate employed by the CODEC 112. It should be noted that in certain applications the sample rate out of the Farrow phase shifter 108 is the same as the sample rate of the CODEC 112, or the Farrow phase shifter 108 may perform some or all of the interpolation in a known manner, thereby eliminating or reducing the need for the interpolator 110.

The transmit signal out of the interpolator 106 is converted from digital to analog by a digital-to-analog (D/A) converter 132 and, then, supplied to a hybrid circuit 114. Also, an analog receive signal from a remote device, e.g., a modem, at the TCCO 100 is supplied via the twisted pair telephone line 102 to the hybrid 114 and, then, to an analog-to-digital (A/D) converter 134 to convert the receive signal from analog to digital. The hybrid circuit 114 is employed to supply the analog version of the transmit signal to a twisted pair telephone line 102 for transmission to a remote modem at the TCCO 100, and to supply an analog version of the receive signal from the remote modem at the TCCO 100 to the modem. Hybrid circuits for interconnecting two-wire to four-wire telephone lines and vice versa are well known in the art, as are their problems and limitations regarding echoes on receive signals.

The sampling rate of the D/A converter 132 and the A/D converter 134 is controlled by a clock 136. In certain embodiments, the clock 136 has a clock rate that is divided several times by a divider 138 to obtain the sampling rate. For example, if the sampling rate is

approximately 32kHz and the clock's rate is approximately 1MHz, the clock 136 can be divided by five (5) divide-by-two dividers 138 to obtain the sampling rate of approximately 32kHz. In certain embodiments, a known add/delete register 140 is used to add or delete one clock cycle from the highest clock rate, e.g., the 1Mhz clock. By adding or deleting clock cycles from a higher rate clock 136, very precise changes to the sampling rate can be achieved. In one embodiment, the addition and deletion of a clock cycle from the clock rate is performed by a phase locked loop 130, which will be described below. In certain embodiments, the D/A converter 132, the A/D converter 134, the clock 136, and the add/delete register 140 are contained within a single CODEC 112.

The receive signal from the A/D converter 134 is supplied to a positive input of an algebraic combining unit 142. A first echo estimate signal generated by the PESC 126 is algebraically subtracted from the received signal by the algebraic combining unit 142 to remove a first portion of an echo on the receive signal, thereby yielding a receive signal and an error signal. The resultant error signal contains only elements related to intersymbol interference and line noise.

The PESC 126 generates the first echo estimate signal for removing the first portion of the echo from the receive signal. The PESC 126 is an adaptive transversal filter that receives the transmit signal out of the Farrow phase shifter 108 at an input and generates the first echo estimate signal at an output. The coefficients for the taps of the adaptive transversal filter are determined using known training protocol and are not updated after training. In use, an impulse response characteristic is generated in the PESC 126, which generates the first echo estimate signal that will eliminate the major portion of any echo signal on the same path as the receive signal.

In certain embodiments, the PESC 126 is implemented using a sub-canceler structure. The coefficients for the taps of the sub-cancelers are trained during a known half-duplex training mode using a known least-mean-square (LMS) algorithm and, specifically, during the "hand shaking" period between the modem depicted in FIG. 1 and a remote modem at the TCCO 100. The selection of a PESC 126 that incorporates an appropriate number of sub-cancelers will be readily apparent to those skilled in the art. In one embodiment, the PESC 126 incorporates four (4) sub-cancelers. Sub-canceler structures are well known adaptive transversal structures that are computationally efficient and can be easily implemented by the DSP 104.

The first error signal out of the algebraic combining unit 142 is supplied to the PLL 130. The PLL 130 is configured to adjust the sampling rates of the D/A converter 132 and the A/D converter 134 through the add/delete register 140 and the clock 136, thereby adjusting the phase of the receive signal. The PLL 130, the clock, 136, the divider 138, and the add/delete register 140 form a timing adjustment circuit for adjusting the sampling rate of the converters 132, 134. If the PLL 130 determines that a clock cycle should be added to the clock 136, the PLL 130 will generate an indicator having a first value that is supplied to the add/delete register 140 to instruct the add/delete register 140 to add a clock cycle to the clock 136. Likewise, if the PLL 130 determines that a clock cycle should be removed from the clock 136, the PLL 130 will generate an indicator having a second value that is supplied to the add/delete register 140 to instruct the add/delete register 140 to remove a clock cycle from the clock 136. By adding/deleting clock cycles, fine adjustments to the sampling rate of the D/A converter 132 and the A/D converter 134 can be performed in a computationally

efficient manner. The development of a suitable PLL 130 will be readily apparent to those skilled in the art.

The receive signal out of the algebraic combining unit 142 is decimated by the decimator 116 to reduce the sample rate, if necessary. The receive signal out of the
5 decimator 116 is then equalized by a fractionally spaced equalizer 118, which is employed to reduce intersymbol interference in a well-known manner. The fractionally spaced equalizer 118 includes an adaptive transversal filter that is responsive to an adaptive signal at an adaptive input. The adaptive signal is based on the input and output of the slicer 120 described below. In certain embodiments, the fractionally spaced equalizer 118 decimates the receive signal in a known manner, or the sample rate does not need to be reduced, thereby
10 eliminating or reducing the need for a separate decimator 116.

The receive signal out of the equalizer 118 is supplied to a positive input of a known algebraic combining unit 144. A second echo estimate signal generated by the PEEC 128 is algebraically subtracted from the receive signal by the algebraic combining unit 144 to
15 remove a second portion of the echo from the receive signal.

The PEEC 128 generates the second echo estimate signal for canceling echoes that arise during the operation of the modem of FIG. 1, such as echoes due to temperature variations in the modem's circuitry. The PEEC 128 is an adaptive transversal filter that receives the transmit signal out of the Farrow phase shifter 108 at an input and an adaptive
20 signal, based on the input and output of the slicer 120 described below, at an adaptive input; and processes the signals to generate the second echo estimate signal at an output. The coefficients for the taps of the adaptive transversal filter are determined using known training protocol and are updated during normal operation of the modem. In use, an impulse response

characteristic is generated in the PEEC 128, which generates the second echo estimate signal to remove remaining echo signals on the same path as the receive signal.

In an embodiment of the invention, the PEEC 128 is utilized in conjunction with the PESC 126. The PESC 126 is employed before the equalizer 118 to cancel a major portion of any echo signal, while the PEEC 128 is employed after the equalizer 118 to cancel echo signals caused by temperature variations of components within the modem. The PEEC 128 may use either a finite impulse response (FIR) filter or an infinite impulse response (IIR) filter. Generally, a long FIR filter can be replaced with a short IIR filter, which is computationally efficient. An example of an echo canceler incorporating a PESC 126 and a PEEC 128 can be found in commonly assigned U.S. Patent No. 6,240,128 to Banerjea et al. entitled Enhanced Echo Canceler, incorporated fully herein by reference.

It will be apparent to those skilled in the art that the PEEC 128 can be employed by itself to combat both the primary echo component and echo components which arise during normal operation of the modem. By employing the PESC 126 to combat the primary echo component, however, the dynamic range of the echo is reduced, which translates into more rapid and more accurate tracking capability by the PEEC 128.

The receive signal out of the algebraic combining unit 144 is supplied to the slicer 120 for "slicing." The slicer 120 is employed in a known manner to compare incoming symbol values to standard symbol values and, then, supply the closest standard symbol value to the current incoming symbol value at an output of the slicer 120. The input to the slicer 120 is subtracted from the output of the slicer 120 by a known algebraic combining unit 146. The resultant signal out of the algebraic combining unit 146 is the adaptive signal that is supplied to the adaptive input of the FSE 118 to adjust its coefficients in a known manner to

minimize intersymbol interference in the receive signal. In addition, the adaptive signal is supplied to the adaptive input of the PEEC 128 to adjust its coefficients.

An output from the slicer 120 is also supplied to the DFE 124 and the receiver 122. The DFE 124 is a known equalizer for removing any residual intersymbol interference in the output from the slicer 120. The receiver 122 demaps and demodulates the standard symbols in the receive signal from the slicer 120 into encoded data bits. The encoded data bits are then descrambled and decoded by the receiver 122, thereby yielding a downstream stream of data 126 for processing by the DSP 104.

Having thus described a few particular embodiments of the invention, various alterations, modifications, and improvements will readily occur to those skilled in the art. For example, the present application has been directed to establishing communication with a device, e.g., a modem, at a TCCO, however, the present invention could be employed to establish communication with devices at essentially any residential or commercial location. In addition, the detailed description focuses on the use of a twisted pair telephone line as the communication medium, however, the present invention may be utilized with other communication mediums such as fiberoptic and wireless communication mediums. Such alterations, modifications and improvements as are made obvious by this disclosure are intended to be part of this description though not expressly stated herein, and are intended to be within the spirit and scope of the invention. Accordingly, the description is by way of example only, and not limiting. The invention is limited only as defined in the following claims and equivalents thereto.